Timing Methods for Depth Determination in Germanium Strip Detectors

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The ability to measure the interaction depth of a gamma ray in a planar germanium strip detector has been demonstrated using various Constant Fraction Discriminators (CFD) and leading edge discriminators. Thick detectors can then be used in Compton telescopes or other detectors that require three-dimensional position resolution. Large systems based on these detectors require many thousands of channels of electronics which necessitates a move to CMOS ASIC readout. Traditional CFDs do not lend themselves to CMOS due to their need for delay lines. Different timing methods better suited for CMOS include leading edge discriminators and falling edge discriminators. The simplest methods seem to work well in the laboratory and indicate that CMOS electronics can be built to read out a thick strip detector with depth resolution. This technique is suitable for a variety of semiconductor detectors.

1. INTRODUCTION

Three-dimensional position resolution in gamma-ray detectors is of special interest in imaging gamma-ray detectors. The depth resolution has been shown to be a factor of three or more better than the strip pitch in a germanium strip detector [1].

The depth of a gamma-ray interaction in planar detectors is proportional to the time difference between the collection of electrons and holes on the opposite faces of the detector. Depth resolution in germanium strip detectors has been demonstrated using an implementation of a Constant Fraction Discriminator (CFD) [1]. A thin beam of 122 keV gamma rays from ^{57}Co was scanned along the side of the detector and the time difference was measured (Figure 1). The CFD was made with a comparator that fired when a 3 db attenuated copy of the original signal and a copy delayed 150 ns cross. A simulation of the signals that are fed into the comparator for the CFD is shown in the middle of Figure 2. Timing methods that do not use an external delay should provide systems that are more compact, lower power, and simpler to fabricate in a CMOS process.

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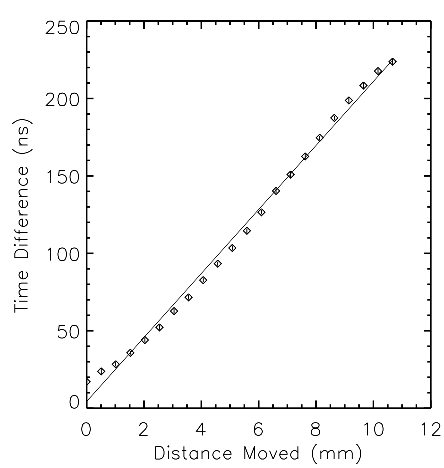

Figure 1. The ^{57}Co fan source was scanned along the side of the detector. Using the CFDs implemented on the NRL NIM module, the timing difference as a function of position was determined. This work was first shown in [1].

2. ELECTRONICS

The depth has been measured in a germanium strip detector in the past [2,3] but these measurements digitized the preamplifier waveform and then manipulated the waveforms in software. This work uses analog electronics to measure the energy and depth of a gamma ray interaction.

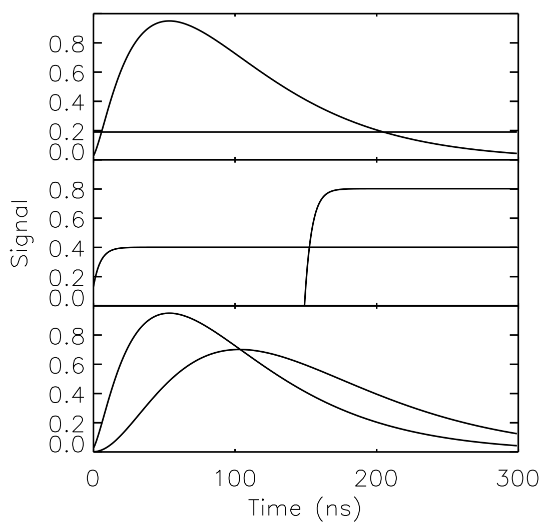

Figure 2. A simulation of the comparator input for the LED, CFD, and FED from top to bottom. The comparator fires when the curves intersect.

A few important components are necessary to measure the time between the charge collection on the two sides of the detector. First, shaping amplifiers and Analog to Digital Converters (ADC) are needed to determine the energy of the interaction. This allows one to compare the energies from both sides of the detector. If the energies from strips on both sides are equal, they resulted from the same interaction. Second, one needs a circuit that produces timing logic signals and a Time to Digital Converter (TDC) to measure the time between logic signals. The shaping circuit, TFA, and multiple types of timing circuits were included in NIM modules designed and built at the Naval Research Laboratory (NRL) [1]. The ADCs and TDCs used to digitize the signals were Phillips CAMAC modules. The germanium strip detector is 5 x 5 x 1.1 cm thick and has 25 strips on each side [4]. The energy resolution using this system at 122 keV was 1.6 keV FWHM while the TDC timing resolution for a pulser was 0.6 ns. The time difference between a gamma ray interaction at the lithium face versus the boron face is about 220 ns for this 11 mm thick detector.

The NRL NIM modules have two other timing methods built in besides a CFD implementation. These circuits are selectable by a set of jumpers. The first circuit takes the Leading Edge Discriminator (LED) signal and uses it as the timing pulse. The second method is sometimes called a Falling Edge Discriminator (FED) and is described in [5,6]. The FED takes a copy of the TFA signal and feeds it into an integrator. The integrated TFA signal and the original TFA signal are then run into a comparator, enabled by the LED, which fires when the two signals cross. This leads to a timing signal on the falling edge of the TFA signal, hence the term FED. Simulations of comparator inputs for all three timing circuits are shown in Figure 2.

3. TIMING METHODS

The three different timing circuits were studied using a 1 mCi ^{57}Co fan source. The fan source produced 122 keV gamma rays from the source passing through a 0.1 mm aperture between two 11.5 cm long tantalum plates. This fan beam was aligned parallel to the faces of the detector and illuminated the side of the detector about 4 mm from the lithium face of the detector. The depth resolution was measured between the lithium strip closest to the source and the middle strip on the boron side. By limiting it to this small region, misalignments and changes in detector impurities or electric fields could be ignored. The gamma-ray beam is 0.15 mm at the edge of the detector and the average electron motion is about 0.1 mm which means that the depth resolution is limited to about 0.2 mm.

3.1. CFD

The NRL NIM modules use a signal from a LED to enable the CFD comparator. The LED logic for each channel on the detector is ORed together to form a common gate. This gate is used to start the ADC and after being delayed by a Phillips Gate and Delay module for 150 ns, as a common stop for the TDC. Each TDC channel is started by the output of the CFD. The threshold of the LED that enables the CFD comparator was set to 35 keV. Operating in this mode, the system had a timing resolution of 14.5 ns.

The NRL NIM modules were reconfigured so that the output of the CFD was ORed together for all detector channels and used as the TDC stop. This system had a timing resolution of 12.5 ns. It was also found that replacing the Gate and Delay module with a length of cable equal to 150 ns of delay, improved the resolution by 0.5 ns. A timing resolution of 12.5 ns corresponds to a depth resolution of 0.6 mm, nearly a factor of 4 better than the strip pitch of 2 mm. Because these changes had such a large effect on the timing resolution, they were used in all of the following tests.

To ensure that the NRL NIM modules implementation of the CFD, as describe in Section 1, was not a source of timing jitter, it was compared to an external CFD. The external CFD (Ortec 935) works in a slightly different manner. The input signal is split in two. One signal is attenuated to 20% of its original value and the other signal is inverted and delayed. The two signals are then recombined and are fed into a zero crossing comparator. The comparator then enables a LED that triggers at some threshold above the zero crossing on the summed signal. Using the external CFD showed a timing resolution of 10.8 ns. This was a 1.7 ns improvement over the the NRL NIM module CFDs. The source of additional timing jitter in the NRL NIM modules is partially due to the implementation of the CFD.

3.2. FED

The Falling Edge Discriminator is easier to implement than the CFD with no need for a delay line. This circuit only needs an RC integrator and one more comparator than a LED. The NRL NIM modules were designed to use an integration time of 50 ns to match the differentiation time of the TFA. Again the comparator enable LED was set to 35 keV. The FED timing resolution was found to be 10.7 ns which is the same as the external CFD system. Longer integration times were tested up to 250 ns but the timing resolution remained the same.

3.3. LED

The Leading Edge Discriminator is the simplest circuit tested. It only needs a TFA for amplification and a comparator with one input connected to the TFA and the other to an adjustable voltage that sets the threshold of the circuit. The LED circuit in the NRL NIM module and a Phillips LED NIM module produced the same depth timing resolution of 9.1 ns. This is the best timing resolution of the methods tested. The LED threshold was tested at both 5 keV and 35 keV, and the timing resolution remained the same.

4. MULTIPLE POSITIONS AND ENERGIES

The preceding tests were all done at one energy and one position for the LED and FED. An ideal discriminator should be immune to changes in pulse shape or amplitude while a simple LED is more likely to be affected. The question we tested is how well does the FED perform?

Multiple gamma-ray lines from a ^{133}Ba source were used. The strongest lines are at 356 keV, 81 keV, 303 keV, 384 keV, 276 keV, in order of decreasing strength. This one source permits examining a number of gamma-ray energies at a fixed position.

The fan beam from the ^{133}Ba illuminated the detector 0.9 mm from the lithium face. The location of the timing peak for each gamma ray line from the ^{133}Ba source was determined. Figure 3 shows the time difference measured for several energies, each interacting at the same depth. The lower set of points in Figure 3 shows that using the LED, threshold at 5 keV, the timing peak moves as a function of energy. The slope of this change is 80 ps/keV. The slope results from slightly different pulse shapes from the lithium and boron side of the detector.

Moving the fan beam to 7.3 mm from the lithium face and repeating the measurement shows a slope of -60 ps/keV as one can see on the top set of points in Figure 3. The slope changes

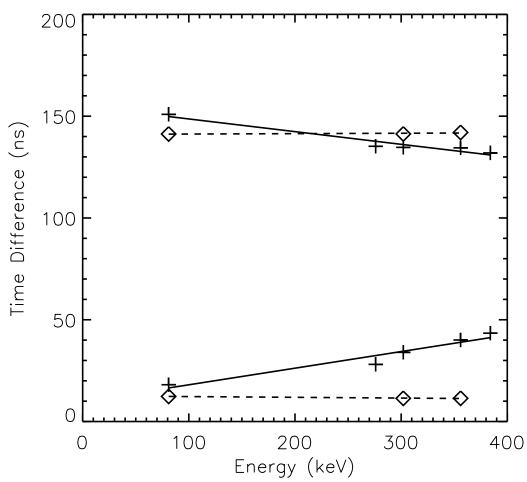

Figure 3. Timing measurements from a ^{133}Ba source at a position 0.9 mm from the lithium face on the bottom and 7.3 mm from the lithium face on the top. The LED timing circuit data points are marked with Xs and have their slope shown with a solid line. The FED timing circuit data is shown with triangles and a dashed line.

sign because the interaction point is now closer to the boron side than the lithium side. If the experiment shown in Figure 1 were repeated with an LED, the slope shown in Figure 1 would change with energy.

Using the FED with a threshold of 35 keV and moving the source back to 0.9 mm from the lithium face one sees a nearly flat response to the different energies with a slope of -4 ps/keV. Repeating the FED measurement at 7.3 mm from the lithium face again shows a nearly flat response, 2 ps/keV, as can be seen in Figure 3. This flat response is due to the FED triggering at the same point on the signal regardless of pulse shape differences.

5. CONCLUSIONS

All three of the timing methods measure the timing resolution adequately. The FED and the external CFD both had timing resolutions of 10.7 ns for the 122 keV gamma ray from ^{57}Co. This corresponds to a depth resolution of 0.5 mm which is a factor of four better than the strip pitch of the detector. The LED shows a timing resolution of 9.1 ns which is slightly better than 0.5 mm at the same energy. The effect of strip pitch on the timing resolution has not been studied.

The CFD and FED do not walk significantly with changing pulse shapes but the LED does. The response of the LED to different energies is linear and could be calibrated and corrected. This effect should be more pronounced in silicon detectors where the difference in electron and hole velocities is larger.

A FED has many desirable features. It is ideal for compact, low power CMOS electronics for use with semiconductor detectors as has been shown by [6]. It has good timing resolution, good rejection of changes in pulse shape, and no need for a delay line. Further tuning of the FED is possible by changing the TFA timings as well as the integration time of the FED or replacing the integrator with a TFA with different timings.

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